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Prospect and potential of biomass power to mitigate climate change: A case study in India

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ABSTRACT

Biomass has often been regarded as a promising renewable energy resource to mitigate climate change. However, what will be the impact on global surface temperature if biomass replace fossil fuel remain unclear. This paper, through a case study in Uttar Pradesh, India address this issue by assessing biomass resource potential to reduce fossil fuel demand and mitigate climate change. Impact of biomass power related GHG emissions on global surface temperature is estimated using the Absolute Global Temperature change Potential (AGTP) climate metric. Uttar Pradesh can produce 71 Mt surplus biomass annually, equivalent to 7298 MW power. Power density of biomass range between 0.10 and 0.25 Wm^{-2}. Significant amount of GHG emissions reduction is possible if biomass replace fossil fuel as a power source in the region. Annual GHG emissions associated with 1 MWh of power derived from coal, natural gas and biomass would cause 4.10×10^{-7}, 2.40×10^{-7} and 1.25×10^{-7} mK rise in global surface temperature, 100 years after an initial emission, indicating potential of biomass power to mitigate climate change. Variation in spatio-temporal distribution and low power density could be delimiting factors in large-scale deployment of biomass power.

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1. Introduction

Biomass is currently the single, largest source of renewable energy worldwide, supplying nearly 9% of the total global primary energy demand (IEA, 2017). In 2016, around 500 TWh of electricity was generated from biomass, accounting for 2% of world electricity generation. In India as of 2017, nearly 8.5 GW of grid connected biomass power have been installed, equivalent to 14% of total installed renewable power capacity of the country (MNRE, 2018). Biomass power potential in India is 23 GW and the top five states (in terms of installed capacity) are Maharashtra, Uttar Pradesh, Karnataka, Tamil Nadu, and Andhra Pradesh (MNRE, 2018). India's biomass program is primarily focused on biofuel (Dhinesh and Annamalai, 2018) and agro-forestry residue-based biomass power (Singh, 2017).

Biomass is a spatio-temporally distributed resource. Biomass power projects are generally occur in a decentralized manner, such as at the local administrative level (village/district). Local inventories on biomass would be more conducive for aligning supply and demand and moderating transportation cost (Liu et al., 2016). Prior knowledge of biomass availability allow power plant management to arrange for alternative fuel during lean period of feedstock supply. Identification of spatial distribution pattern of biomass help optimizing supply-chain, which in turn reduce logistics cost (Ko et al., 2018). Knowledge of power density is also important for biomass supply-chain logistics consideration. Such database are not readily available for many regions of India, jeopardizing long-term viability of biomass programs of the country.

Like fossil fuels, biomass power generation also result in GHG emissions, but less than its fossil counterpart (Cherubini et al., 2009). The climatic impact of GHG emissions is commonly expressed in Global Warming Potential (GWP) climate metric. Although the name suggest, however GWP does not lead to equivalence with temperature or other climate variables (Myhre et al., 2013). As alternative, Shine et al. (2005) proposed the Global Temperature change Potential (GTP) climate metric to

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explain the impact of emissions on surface temperature. This enables better climate change mitigation policy making. The UNEP/SETAC has also recommended GTP in life cycle assessment (LCA) of renewable energy (UNEP/SETAC, 2016).

The present study is conducted in the state of Uttar Pradesh, India to assess (i) biomass availability, distribution and power generation potential, (ii) power density of biomass, and (iii) GHG emissions from biomass power generation and its impact on global surface temperature. Novelties of the research are: (i) detailed, up to district-level resolution biomass resource inventory (crop residue, livestock manure and plantation biomass) has been prepared for Uttar Pradesh, India, (ii) assessment of power density of biomass feedstocks is new in India, and (iii) the study goes beyond merely quantifying GHG emissions but link emissions with AGTP (Absolute GTP) to assess impact on global surface temperature change over 100 years. The biomass emissions and temperature response are compared with coal and natural gas-fired power generation systems.

2. Energy mix of Uttar Pradesh, India

Uttar Pradesh is the most populous state of India and the 2nd largest in terms of geographical area. The state is divided into 75 districts. Coal-based power generation dominate energy mix of the state (81% of the total power demand) (NPP, 2018). Contribution of renewable energy is 2.7 GW, of which biomass and bagasse cogeneration-based grid connected capacity is about 1.9 GW (MNRE, 2018). The state produces the largest amount of sugarcane in India and increase in bagasse cogeneration capacity could be expected in near future. The contribution of small hydro and solar (grid connected) are 25.1 and 550 MW (MNRE, 2018). Despite many efforts to harness both renewable and non-renewable energy, the state is still facing electricity crisis. For example, during April 2017 to March 2018, there was a shortage of 2213 MW of power supply during peak demand period (CEA, 2018). Additional power generation utilizing locally available biomass resources could be a potential solution to improve energy situation of the state.

3. Methods

Biomass resource and power potentials are assessed for all the 75 districts of Uttar Pradesh. Power density of selected biomass feedstock is also estimated. GHG emissions from biomass power generation is estimated using IPCC data (Schlömer et al., 2014; Bruckner et al., 2014) and relevant literature (Spath et al., 1999; Spath and Maan, 2000; Oreggioni et al., 2017; Iordan et al., 2016). Impact of emissions on global surface temperature change is estimated using AGTP climate metric. Biomass emissions and its climatic impacts are compared with coal and natural gas-fired power generation systems (Schlömer et al., 2014; Bruckner et al., 2014).

3.1. Assessment of biomass resources and power generation potentials

Three biomass power systems *viz*. crop residue, livestock manure and plantation biomass are considered (see Supplementary material 1 for detail). In crop residue biomass system, 28 different types of residues are selected for analysis. In livestock manure, four livestock categories *viz*. cattle, buffalo, goat and sheep (together), and pig are considered. The livestock are grouped as juvenile and adult. In plantation biomass, *Acacia nilotica* (local name *babul*) is selected as potential plantation tree species. The plantation is considered only in selected marginal land of the study area, identified through the Wasteland Atlas of India (DLR, 2017). In all the cases, biomass power potential is estimated taking conservative values to avoid exaggeration. The method (similar to biomass assessment of Hiloidhari et al., 2014) is further explained in Table 1.

3.2. Assessment of power density of biomass

Power density (Wm^{-2}) is the amount of power attributed by an energy source in a given physical area. It is straightforward to determine power density of crop residue and plantation biomass however, in case of livestock manure, one need to know the feed contributing area for manure. The feeding practices vary with animal type and with the nature of farm. For example, stall feeding and open grazing are two common practices in India. Misri (2017) reported that 4% of the total cultivable land in India is used for animal fodder production. Livestock also grazed on other grassland and pasture areas. It is projected that 5% of the total cultivable land in Uttar Pradesh is used for livestock feed production.

The power density is determined by dividing the estimated biomass power potential with respective land area contributing to biomass feedstocks as below:

$$PD_B(i,\ j) = \frac{BP(i,j)}{A(i,j)} \quad (1)$$

$PD_B(i,j)$ is power density of biomass, Watt m^{-2}; $BP(i,j)$ is biomass power, Watt; $A(i,j)$ is biomass contributing land area, m^2. Here, i and j represents individual biomass type and district.

3.3. Comparative GHG emissions from biomass and fossil power generation

There are various activities required to support biomass power generation. The entire power generation process can be divided into two parts: feedstock production and power generation. Feedstock production involves unit operations such as land preparation, crop/plant/livestock production, harvest, collection and transportation. Power generation includes conversion of feedstock into heat and then into power. There also involve auxiliary operations like pre-processing of feedstock and by-product management (disposal/recycling). All such unit operations require inputs of machinery, energy, and materials in various forms, contributing to emissions. It is difficult to get actual emission estimates case-by-case basis. In absence of site-specific emissions inventories for various operations as stated, IPCC data (Schlömer et al., 2014; Bruckner et al., 2014) and other literature (Spath et al., 1999; Spath and Maan, 2000; Oreggioni et al., 2017; Iordan et al., 2016) were used as explain below and in Table 2.

Life cycle assessment (LCA) studies of biomass power generation in India are limited. The IPCC 5th Assessment Report (AR5) (Schlömer et al., 2014; Bruckner et al., 2014) was consulted to estimate GHG emissions from biomass power generation in the study area in comparison with coal and natural gas. The Chapter 7 of the Working Group III of IPCC AR5 present a synthesis of hundreds of life cycle GHG emissions studies both for renewable and non-renewable energy systems. The report grouped emissions into three categories: low, median and high. Application of IPCC data in this study is described below:

(i) Median emission values (as per IPCC AR5) are considered to estimate GHG emissions. Low and high emissions values are used in sensitivity and uncertainty analysis.
(ii) Emissions values reported in IPCC AR5 are in CO_2eq unit (*i.e.* in GWP term). This measurement of emissions in GWP could not be directly used in the current study because CO_2eq unit does not tell the contribution of individual GHG to the total emissions value. Relevant LCA literature (Spath et al., 1999; Spath and Maan, 2000; Oreggioni et al., 2017; Iordan et al.,

Table 1
Models to assess biomass resource and power potentials.

Biomass power system	Model	Parameter details	Model descriptions
Crop residue	$CRB(j) = \sum_{i=1}^{n} RPR(i,j) \times Y(i,j) \times A(i,j) \times F(i,j)$ (Model 1)	$CRB(j)$ is crop residue biomass, t (tonne); $RPR\ (i,j)$ is residue production ratio; $Y\ (i,j)$ is crop productivity, t ha^{-1}; $A\ (i,j)$ is crop area, ha; $F\ (i,j)$ is residue availability factor. Here, i and j represents individual crop and district.	Model (1) determines crop residue biomass potential in a given area. It consider factors such as residue production ratio (RPR, residue production per unit of grain production), crop area, crop productivity and residue availability factor. The RPR for different crop residues are given in the Supplementary material 1. District-level crop area and crop productivity for the period of 2015–2016 are collected from the Ministry of Agriculture, India (MoA, 2017). The residue availability factor is the amount of residue available for power generation after deducing the competing uses (e.g., feed for animal, soil requirement). Residue availability factor for selected residues are given in Supplementary material 1.
	$BP_{CRB}(j) = \frac{\eta \times \sum_{i=0}^{n} RPR(i,j) \times Y(i,j) \times A(i,j) \times F(i,j) \times LHV(i)}{T}$ (Model 2)	$BP_{CRB}\ (j)$ is biomass power potential from crop residue biomass, MW; η is net conversion efficiency (fuel to power), $LHV(i,j)$ is lower heating value of fuel, MJ t^{-1}; T is power plant operation time, sec y^{-1}. Here, i and j represents individual crop and district.	Model (2) is used to estimate power generation potential of biomass. Net conversion efficiency (fuel to power) is taken as 25% (McKendry, 2002). Continuous operation of biomass power plant throughout the year is considered.
Livestock manure	$LMB(j) = \sum_{i=0}^{n} P(i,j) \times Y(i,j) \times F(i,j) \times D(i,j)$ (Model 3)	$LMB\ (j)$ is livestock manure biomass, t; $P\ (i,j)$ is livestock population, thousands; $Y(i,j)$ is manure yield, kg $animal^{-1}$ day^{-1}; $F\ (i,j)$ is manure availability factor; $D\ (i,j)$ is dry matter fraction of manure. Here, j and i represents individual district and livestock.	Model (3) estimates livestock manure biomass potential in a given area. District-level livestock data are collected from the Department of Animal Husbandry, Dairying and Fisheries, Government of India (DADF, 2017). Manure availability factor is taken as 0.5. See Table 1 of Supplementary material 1 for detail.
	$BP_{LMB}(j) = \frac{\eta \times \sum_{i=0}^{n} P(i,j) \times Y(i,j) \times F(i,j) \times D(i,j) \times B(i,j) \times M \times LHV}{T}$ (Model 4)	$BP_{LMB}(j)$ is biomass power potential from livestock manure, MW; $B(i,j)$ is specific biogas yield, m^3 kg^{-1}; M is methane (CH_4) fraction in biogas; LHV is lower heating value of CH_4, MJ m^{-3}; η is net conversion efficiency; T is power plant operation time, sec y^{-1}. Here, j and i represents individual district and livestock.	Model (4) determines manure biomass power potential in a given area. CH_4 fraction of manure, heating value of CH_4 and net conversion efficiency (fuel to power) are taken as 0.6 and 35.78 MJ m^{-3}, and 33% (Brahma et al., 2016). Continuous operation of power plant is considered.
Plantation biomass	$ln(AGB) = a + bln(D) + ln(\rho)$ (Model 5)	AGB is above ground biomass, t $tree^{-1}$ $annum^{-1}$; a and b are the model's fitted parameters, $a = -1.083$, and $b = 2.266$; D is diameter at breast height, cm; ρ is wood specific density, g cm^{-3}.	In model (5), plantation of *Acacia nilotica* tree is considered in selected marginal land of the study area. District-level marginal land distribution data are taken from (DLR, 2017). Above ground biomass (AGB) available from *Acacia* plantation is estimated according to biomass allometric model developed by Chave et al. (2005). Diameter at breast height (D) is taken as 7 cm after 4th year of the plantation (Singh and Toky, 1995). Wood specific density (ρ) is taken as 0.64 g cm^{-3} as per (ICRAF, 2016; UNFCCC, 2018).
	$AGBp_{(j)} = A(j) \times D_{(p)} \times AGB \times R_{(s)} \times F_{(pb)}$ (Model 6)	$AGBp_{(j)}$ is plantation biomass potential, t ha^{-1}; $A(j)$ is area of plantation, ha; $D_{(p)}$ is plantation density, tree ha^{-1}; AGB is above ground biomass, t $tree^{-1}$ y^{-1}; $R_{(s)}$ is plant survival rate; $F_{(pb)}$ is biomass availability factor. Here, j represents individual district.	Model (6) determines amount of above ground plantation biomass available for power generation. Only 70% of the above ground biomass is considered as net feedstock available for power generation. Leaving behind a fraction of biomass (e.g. foliage, needles, and barks) on the forest floor can compensate nutrient losses from biomass removal (Giuntoli et al., 2015).
	$BP_{WLB}(j) = \frac{\eta \times AGBp(j) \times LHV}{T}$ (Model 7)	$BP_{WLB}(j)$ is power potential from plantation biomass, MW; $AGBp\ (j)$ is biomass available for power generation, t; LHV is lower heating value of biomass, MJ t^{-1}; η is net conversion efficiency; T is power plant operation time, sec y^{-1}. Here, j represent individual district.	Statistics available from models (5) and (6) are used with model (7) to determine power generation potential of plantation biomass at district-level. Heating value of *Acacia* and power plant conversion efficiency are taken as 19.57 MJ kg^{-1} (Goel and Behl, 1996) and 30% (Kumar et al., 2015). Continuous operation of biomass power plant is considered. Other details are given in Table 1 of Supplementary material 1.

Table 2
GHG emissions factors for biomass, coal and natural gas-fired power generation systems.

Energy system	CO_2, g kWh−1	CH_4, g kWh−1	N_2O, g kWh−1	Description
Plantation biomass	224.94	0.047	0.012	(i) IPCC AR5 (Schlömer et al., 2014; Bruckner et al., 2014) reported that life cycle GHG emissions (including biogenic and surface albedo) from biomass (dedicated energy crops and crop residue) power generation range from 130 to 420 g CO_2eq kWh−1 with a median value of 230 g CO_2eq kWh−1. Median emissions value was used in this study. (ii) In biomass power generation system, Oreggioni et al. (2017) reported that 97.8% emissions (considering both supply-chain and biogenic emissions) occur as CO_2; while 0.7% and 1.5% emissions resulted as CH_4 and N_2O. Power generation stage is responsible for the highest climatic impact (89.4%), followed by biomass transport (4.8%), biomass chipping (2.5%) and biomass production (3.2%). (iii) Taking reference of IPCC AR5 and Oreggioni et al. (2017), individual GHG-level emissions of CO_2, CH_4 and N_2O are estimated as 224.94, 0.047 and 0.012 g kWh−1. In GWP term, the emissions are 224.94, 1.610 and 3.450 CO_2eq kWh−1 for CO_2, CH_4 and N_2O.
Crop residue biomass	224.94	0.047	0.012	(i) The emissions values estimated for plantation biomass are also used for crop residue biomass according to IPCC AR5 guideline.
Manure biomass	86.00	4.35	0.38	(i) IPCC AR5 (Schlömer et al., 2014; Bruckner et al., 2014) reported that life cycle emissions (including biogenic emission and surface albedo) from biogas system (manure and dedicated crops) range from 130 to 420 g CO_2eq kWh−1 with median value of 344 g CO_2eq kWh−1. Median emissions value was used in this study. (ii) According to Iordan et al. (2016), 43% emissions (both fossil and biogenic emissions) from biogas system occur as CH_4, while 33% and 25% emissions result as N_2O and CO_2. The digested management phase is responsible for the highest climatic impact (61%), followed by biogas production (32%) and biogas combustion (7%). (iii) Based on IPCC AR5 and Iordan et al. (2016), individual GHG-level emissions of CO_2, CH_4 and N_2O are estimated as 86, 4.25 and 0.38 g kWh−1. In GWP term, the emissions are 86, 144.48 and 113.52 CO_2eq kWh-1 for CO_2, CH_4 and N_2O.
Coal	803.76	0.44	0.0037	(i) IPCC AR5 (Schlömer et al., 2014; Bruckner et al., 2014) reported that life cycle emissions (including surface albedo effect) from coal-fired power system ranges from 740 to 910 g CO_2eq kWh−1 with median value of 820 g CO_2eq kWh−1. Median emissions value was in this study. (ii) Spath et al. (1999) in a life cycle study of coal-fired power plant reported that 98.02% of the total GHG emissions is contributed by CO_2, and only 1.842% and 0.134% emissions are contributed by CH_4 and N_2O. Nearly 96% of total CO_2 emission occurs from power plant operation stage, followed by 2%, 1% and 1% from transportation, construction and coal mining processes. (iii) Based on Spath et al. (1999); Schlömer et al. (2014); Bruckner et al. (2014), individual GHG-level emissions of CO_2, CH_4 and N_2O are estimated to be 803.76, 0.44 and 0.0037 g kWh−1.
Natural gas	431.69	1.715	0.000658	(i) IPCC AR5 (Schlömer et al., 2014; Bruckner et al., 2014) reported that life cycle emissions (including surface albedo effect) from natural gas (combined cycle) power system range from 410 to 650 g CO_2eq kWh−1 with median value of 490 g CO_2eq kWh−1. Median emissions value was for the current analysis. (ii) Spath and Maan, 2000 in a life cycle study of natural gas-fired power plant reported that of the total GWP, 88.1% is contributed by CO_2, 11.9% by CH_4 and 0.04% by N_2O. About 74% of CH_4 is emitted as fugitive emissions. Overall, of the total GWP, power plant operation account for 74.6% emissions, followed by 24.9%, 0.4% and 0.1% from natural gas production and distribution, construction and decommissioning of the power plant, and ammonia production & distribution. (iii) Based on Spath and Mann (2000); Schlömer et al. (2014); Bruckner et al. (2014), individual GHG-level emissions of CO_2, CH_4 and N_2O are calculated to be 432.69, 1.715 and 0.000658 g kWh−1.

2016) are reviewed to assess contribution of individual GHGs (CO_2, CH_4 and N_2O) to the total emissions (Table 3).

(iii) The above explanation of GHG emissions estimation can be summarized through Equation (9):

$$E_{(i)} = \sum_{i=0}^{n} \left(P_{(j,k)} \times E_{(i,\,j,k)} \right) \times 10^{-3} \quad (2)$$

$E_{(i)}$ is GHG emissions, kg y^{-1}; $P_{(j,k)}$ is power generation, kWh y^{-1}; $E_{(i,\,j,\,k)}$ is emission factor, g kWh^{-1}. Here, i, j, k represents individual GHG (CO_2, CH_4, N_2O), district and power generation system (*i.e.* biomass, coal and natural gas).

3.4. Impact of GHG emissions on global surface temperature change

Absolute Global Temperature change Potential (AGTP) climate metric (Shine et al., 2005) is used to estimate the impact of power generation-related GHG emissions on global surface temperature change. AGTP reflects the change in global surface temperature at a chosen time in response to an emission pulse, relative to the temperature change due to the emission of equal amount of CO_2 (Shine et al., 2005). The calculated year-by-year AGTP values of CO_2, CH_4 and N_2O for 100 years are presented in Supplementary material-S2 (AGTP models are given in Supplementary material 1).

Annual emissions of CO_2, CH_4 and N_2O (estimated through Eq. (9)) are multiplied with the annual AGTP values to arrive at the global surface temperature change (ΔT) caused by GHG emissions as given below:

$$\Delta T_t = E_{(i)} \times AGTP \quad (3)$$

ΔT_t is the global surface temperature change, K (Kelvin) in time t.

Table 3
Crop calendar of some major crops grown in Uttar Pradesh, India.

Crop	Sowing/Planting	Harvesting
Rice/paddy	June–July	October–November
Wheat	October–January	April
Sugarcane	September–October and February–March	Takes about one year to mature
Maize	June–July	September
Mustard	October	February–March
Arhar/Tur	June	December
Bajra	July	October–November
Lentil	October–November	March
Ground nut	July	October–November

$E_{(i)}$ is GHG emission, kg. The AGTP values (in K kg^{-1}) are given in the Supplementary material-S2.

3.5. Sensitivity and uncertainty analysis

The availability and type of biomass can greatly influence the power generation potential of a region. Variations in heating value of biomass fuels, power plant conversion efficiency also affect the outcome. Variations also exist in GHG emissions among different biomass conversion technologies.

It is challenging to assess the influence of each parameter individually. Feedstock availability and power plant conversion efficiency are the two critical factors affecting the final power output. Basic sensitivity analysis was performed considering two scenarios: (1) low biomass availability factor and low conversion efficiency, and (2) high biomass availability factor and high conversion efficiency (see Supplementary material 1).

Variations in GHG emissions are assessed separately. Low and high levels of GHG emissions from biomass power generation are compared with median level of emissions from coal and natural gas-fired power generation (see Supplementary material 1).

4. Results and discussion

Biomass feedstocks availability in all the 75 districts of Uttar Pradesh, India and their power generation potential, associated

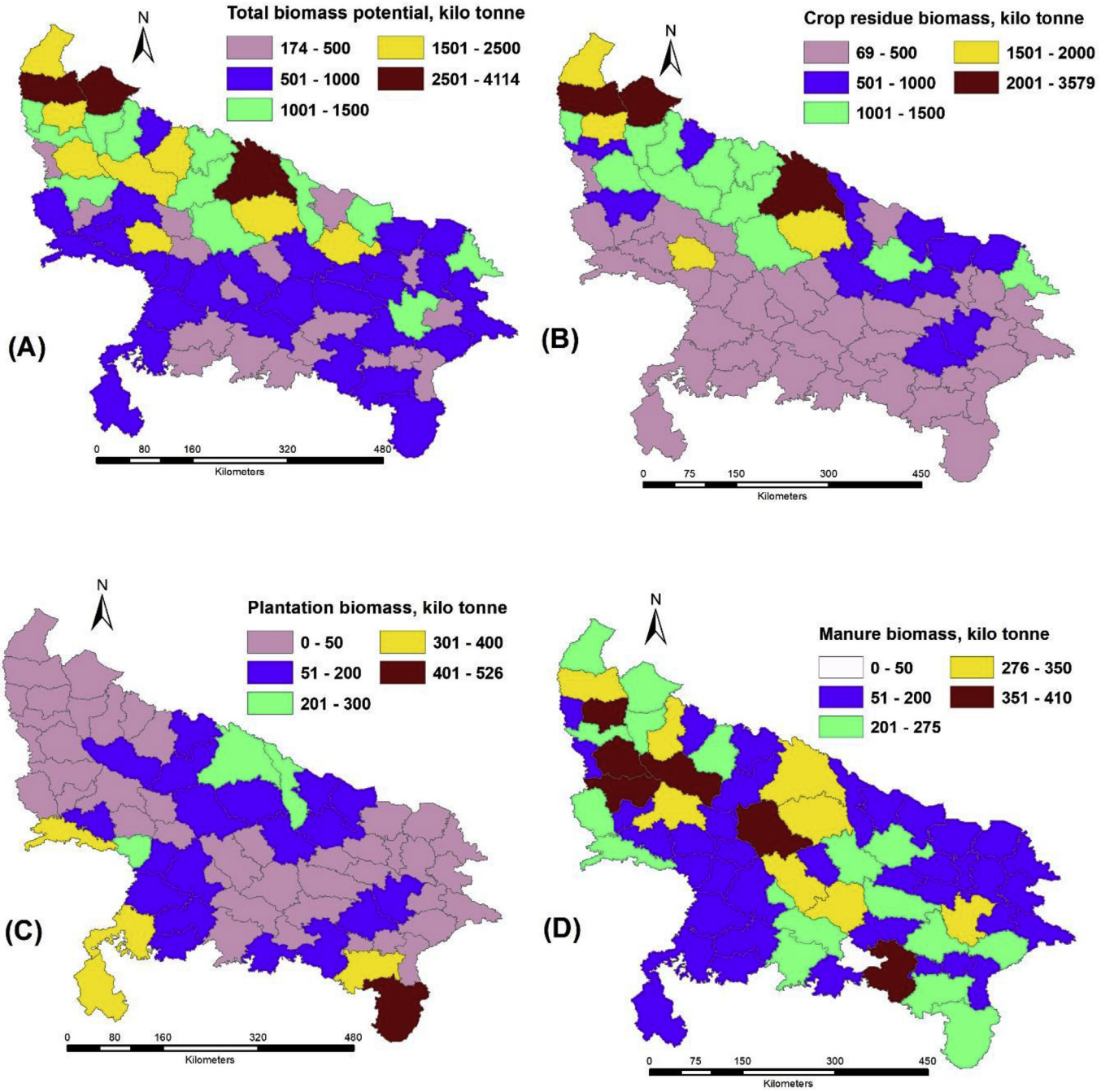

Fig. 1. District-wise biomass resource potential in Uttar Pradesh, India (Figure (A): total biomass potential (crop residue, plantation and manure biomasses); Figures (B), (C) and (D): biomass-wise potential).

GHG emissions and impact on global surface temperature change are discussed below.

4.1. Biomass feedstocks availability and power generation potential

Annual surplus biomass potential in Uttar Pradesh is 70.63 Mt. District level potential is presented in Fig. 1. Crop residues contribute the largest potential (51.34 Mt) with a district level variation of 69.4–3579 kt (kilo tonne). Among the crop residues, the largest contribution comes from sugarcane bagasse (27.05 Mt), followed by wheat (11.13 Mt) and rice (9.46 Mt). Manure biomass potential is 14.24 Mt with variation of 88–410 kt among the districts. Plantation biomass potential is 5.05 Mt with district level variation ranging from 0.013 to 526 kt. At national level also, crop residues contribute the major share of biomass pool in India. Estimates suggest that India has a potential to produce 511 to 684 Mt of crop residue biomass on annual basis (Hiloidhari et al., 2014; Cardoen et al., 2015; Kumar et al., 2015). According to Hiloidhari et al. (2014) gross crop residue biomass potential in India is 686 Mt and 234 Mt is available as surplus for energy generation. Cardoen et al., 2015 reported national level gross crop residue potential as 611 Mt, of which 158 Mt can be considered as surplus. According to Kumar et al. (2015) about 511 Mt crop residues are available as biomass feedstock for power generation in India.

Similar to spatial variation (Fig. 1) in biomass availability, there also exists temporal variation, mostly in crop residues. Table 3 enlists some major crops grown in Uttar Pradesh with their crop calendar. Such temporal variation necessitate prior assessment of existing power supply-demand scenario of a region to optimize biomass power plant output.

Annual primary energy potential from the available surplus biomass in Uttar Pradesh is 0.97 EJ (EJ), equivalent to 3.9% of primary energy consumption in India (24.80 EJ) in 2013 (EIA, 2018). The annual biomass power potential in Uttar Pradesh is 7028 MW, with district level variation ranging from 15.80 to 353.36 MW (Fig. 2). Crop residues contribute the largest potential of 4994 MW. Among the crops, sugarcane bagasse (1930 MW), wheat (1513 MW) and rice (1032 MW) together contribute 92% of crop residue biomass power. Manure biomass power potential is 1094 MW, with district level variation of 6.74–31.14 MW. Plantation biomass power potential is 940 MW with district level variation of 0.17–97.85 MW. Among the all 75 districts of the state, 29 districts have biomass power potential >100 MW, another 28 districts have potential in the range of 50–100 MW and the remaining 18 districts have potential in between 15 and 50 MW (Fig. 3 and supplementary material-S1). Nearly 2065 MW of grid connected biomass power have already been installed in Uttar

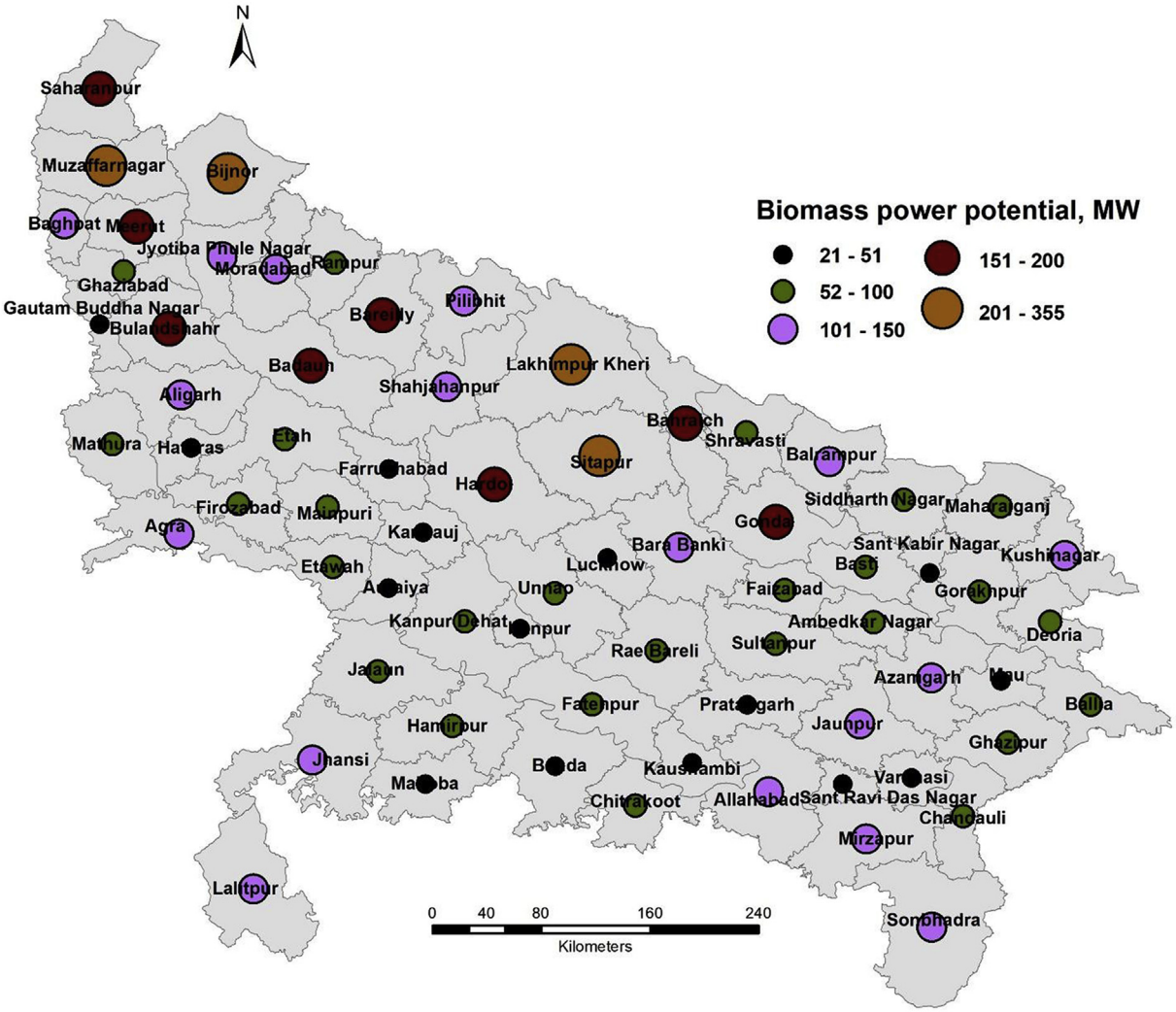

Fig. 2. Spatial variation in biomass power potential among the districts of Uttar Pradesh, India.

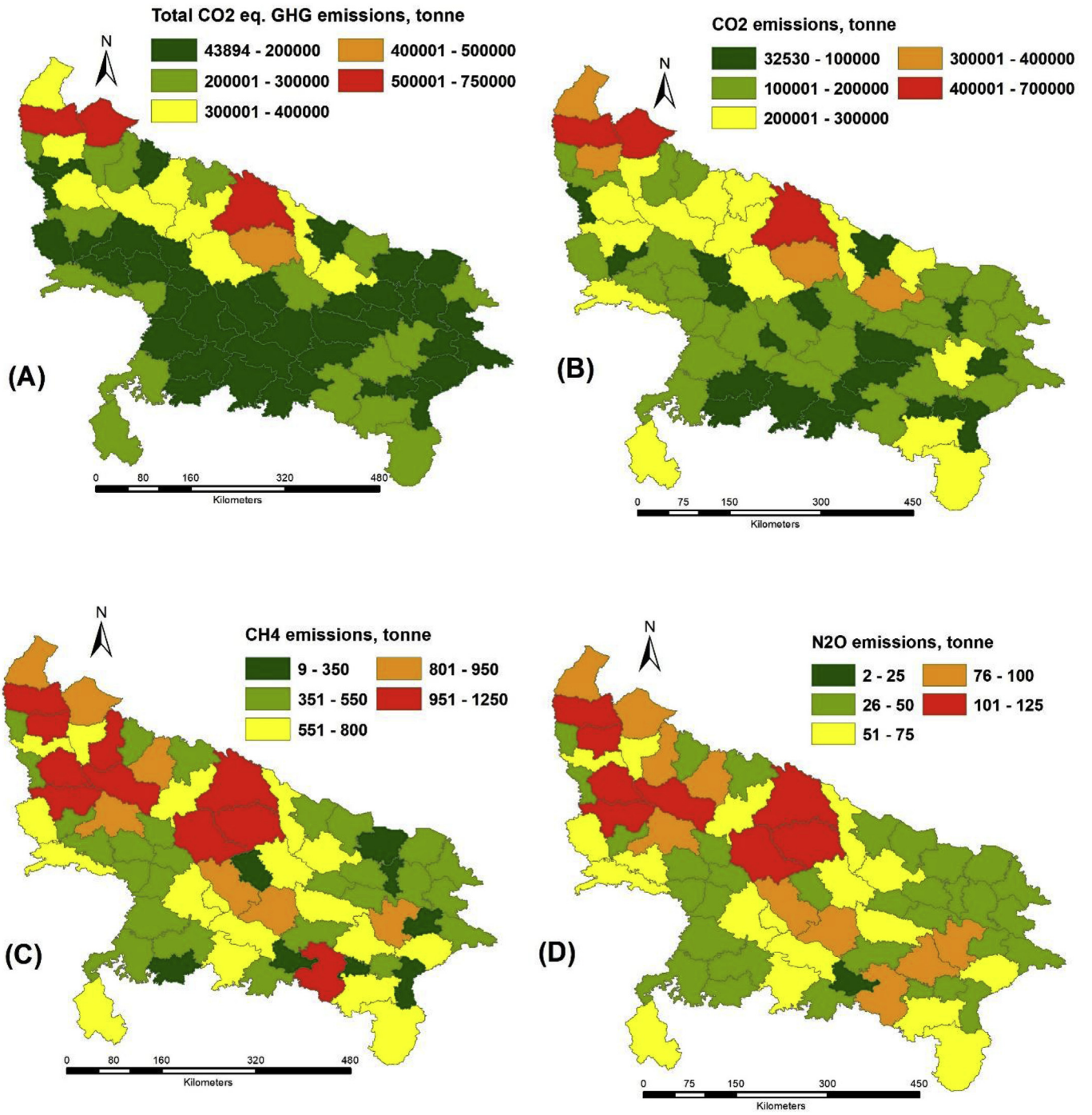

Fig. 3. Potential GHG emissions from biomass power generation in the districts of Uttar Pradesh, India (Figure (A): total GHG emissions (CO_2, CH_4 and N_2O) in tonne CO_2eq; Figures (B), (C) and (D): CO_2, CH_4 and N_2O emissions in tonne).

Pradesh as of 2017. Majority of the commissioned projects are based on sugarcane bagasse (*via* cogeneration route). Sugar mills uses bagasse to generate process heat (steam) and electricity for *in-situ* consumption in sugarcane processing. The surplus is sold to the public grid.

The current assessment of biomass power potential in Uttar Pradesh differ with the estimate of Biomass Resource Atlas of India (BRAI, 2004). As per the BRAI, annual surplus biomass resource (agro residues and biomass from forest and wasteland) and power potentials in Uttar Pradesh are 65800 kt and 2260 MW, much lower than the current estimates. The differences could not be verified. Estimate available from the BRAI is of decade old (generated in 2000–2004) with no recent update. Further, BRAI estimate did not consider biomass power potential of livestock manure. It is also not clear whether BRAI considered sugarcane bagasse cogeneration potential in Uttar Pradesh.

There are pros and cons of using biomass as energy feedstocks (Table 4) with reference to Indian conditions. Such problems are generally localized in nature and can be resolved with appropriate managerial intervention.

Table 4
Some merits and demerits of biomass as energy feedstock.

Sl. No.	Demerits	Merits
1	Crop residue enhances soil fertility (Blanco-Canqui and Lal, 2009) and hence its removal can be detrimental to soil health. In presence of residue-utilizing biomass power plant, removal of residue has to be compensated by additional application of fertilizer to maintain crop productivity. Chemical fertilizer is a major source of agricultural N_2O emission (Crutzen et al., 2016). Increased fertilizer application can reduce/offset the emission savings benefits of bioenergy.	1) India produces large quantity of crop residue. Open burning of residue has become a serious air pollution issue (Vijayakumar et al., 2016). Farmers in crop-intensive states like Uttar Pradesh, Punjab, and Haryana burn residue immediately after grain harvest to clear the field for next cropping. The burning of residue in these states has been reported as major source of air pollution in Delhi, the capital of India (NASA, 2015). On-field residue decomposition contribute to CH_4 emission which is more potent GHG than CO_2 (Sander et al., 2014). Biomass power generation using crop residue is a win-win solution to reduce air pollution and increase energy security with added economic value for farmers.
2	The removal of woody biomass could alter forest carbon dynamic. When a long-standing forest is harvested for energy purpose, carbon payback time of such energy utilization pathway can be as long as hundreds of years (Gibbs et al., 2008).	Annual or short-rotation crops can sequester carbon within very short time period. Suitable short-rotation trees can be planted in marginal land with minimal crop care and nutrient requirement (Schweier et al., 2017). Energy tree plantation in marginal land can ensure energy security and environmental protection.
3	Animal manure is used as organic fertilizer. Diverting organic fertilizer to produce energy would result in additional chemical fertilizer use and more agricultural emission.	Digestate available from manure-based power production system is rich in soil nutrient, which can be recirculated to crop field (Giuntoli et al., 2016). Using digestate as fertilizer is more beneficial in emission reduction than raw manure (Iordan et al., 2016).
4	Biomass has competing uses. Crop residue is used as heating/cooking fuel, animal feed in rural areas of developing countries.	Policy support for improved biomass cookstove, subsidies LPG for poor families can reduce dependency on biomass fuel and increase feedstock availability for modern bioenergy. India has been implementing such policies at national level.

4.2. Power density of biomass

Power density reflects the nature of distribution of energy feedstocks over land areas. The comparison of power densities among different biomass feedstocks as well as geographical regions have relevance because it offer more insight into cost, infrastructure and land demand for setting a renewable energy firm. The estimated power densities of various biomass feedstocks in Uttar Pradesh range from 0.105 to 0.252 Wm^{-2} with an average of 0.129 Wm^{-2}. District level variations in power densities of selected biomass feedstocks are presented in Supplementary material-S1.

Power densities of rice and wheat residues range from 0.006 to 0.024 Wm^{-2}; and 0.007 to 0.179 Wm^{-2}. Power density of these crop residues is < 0.05 Wm^{-2} in majority of districts. Power density of sugarcane bagasse range between 0.06 and 0.1 Wm^{-2} with majority of district having >0.08 Wm^{-2}. For manure biomass, power density varies between 0.04 and 0.40 Wm^{-2} among the districts. Power density of plantation biomass in all the districts is 0.25 Wm^{-2} (uniform level of plantation biomass yield was considered for all the districts). Power density results show that plantation biomass, livestock manure and sugarcane bagasse have higher energy yield per unit of land than other biomasses in the study region.

Power densities of biomasses of the study area are also compared with literature. Smil (2010) reported that power density of woody biomass in the US ranges from 0.5 to 0.6 Wm^{-2}, two times higher than present finding for plantation biomass (0.25 Wm^{-2}). The variation could be due to differences in parameters used to estimate power density. Smil (2010) considered a fuel to power conversion efficiency of 35%, while 30% efficiency is considered in the current study. For crop residues, Kammen and Sunter (2016) reported that power densities of conventional biomass crops ranges from 0.05 to 1.7 Wm^{-2}. Ferguson (2008) mentioned power density of ethanol from Brazilian sugarcane as 2.9 kW ha^{-1} (*i.e.* 0.29 Wm^{-2}). At global scale, de Castro et al. (2014) reported that net power density of biofuel is less than 0.073 Wm^{-2}.

Compared with fossil fuels, power densities of renewable resources are significantly low (Table 5). Power densities of conventional biomass crops, solar PV and wind energy are in the range of 0.05–1.7 Wm^{-2}, 10–120 Wm^{-2} and 2.5–30 Wm^{-2} (Kammen and Sunter, 2016). Power densities of coal and natural gas range

Table 5
Power density of different energy sources.

Energy type	Power density, Wm^{-2}		Source
	Minimum	Maximum	
Rice residue	0.006	0.024	This study
Wheat residue	0.007	0.18	
Sugarcane bagasse	0.06	0.1	
All crop biomass	0.024	0.1	
Livestock manure	0.04	0.41	
Plantation biomass	0.25	0.25	
All biomass	0.11	0.25	
Woody biomass	0.5	0.6	Smil (2010)
Conventional biomass crops	0.05	1.7	Kammen and Sunter (2016)
Brazil sugarcane biofuel	0.29	0.29	Ferguson (2008)
Brazil biofuel	0.3	0.36	de Castro et al. (2014)
Waste to energy	4.1	10	Kammen and Sunter (2016)
Solar PV	10	120	Kammen and Sunter (2016)
Solar thermal	67	240	Kammen and Sunter (2016)
Geothermal	40	100	Kammen and Sunter (2016)
Wind	2.5	30	Kammen and Sunter (2016)
Coal	100	1000	Smil (2010)
Natural gas	200	2000	Smil (2010)

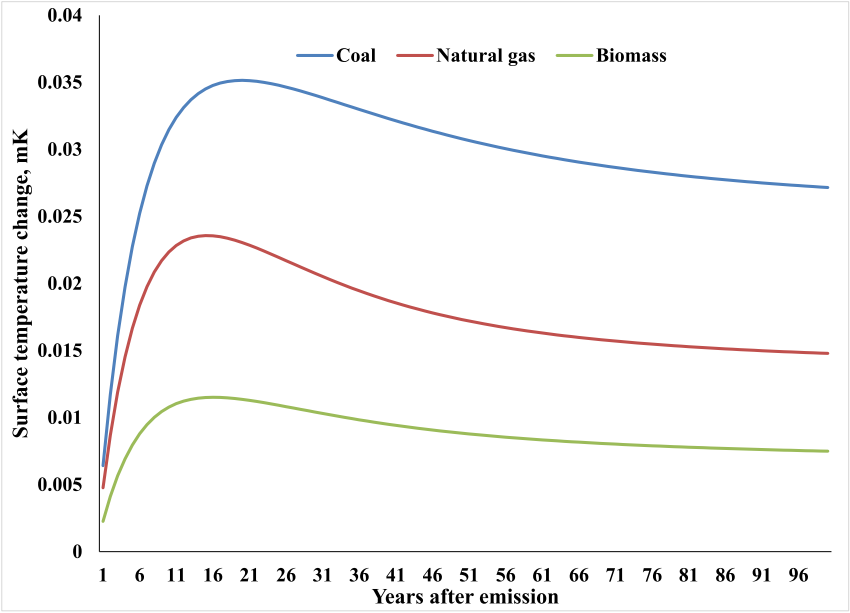

Fig. 4. Global surface temperature change due to a single year's GHG emissions from coal, natural gas and biomass power in Uttar Pradesh, India (surface temperature response of CO_2, N_2O and CH_4 emissions are added together for each energy systems).

in100–1000 Wm^{-2} and 200–2000 Wm^{-2} (Smil, 2010). The lower the power density, higher would be land demand to install renewable power plant to replace an equivalent amount of power drawing from fossil fuels. The relatively low power densities of renewable power may, argue for a prudent and necessary increase in fossil fuel-based energy productions if one weighs in this critical factor.

4.3. Comparative GHG emissions from biomass and fossil power generation

Annual biomass power potential in Uttar Pradesh is 7028 MW. Generation of this amount of biomass power would lead to annual emissions of 12.52, 0.0432 and 0.0043 Mt of CO_2, CH_4 and N_2O. In GWP term, the emissions would be15.16 Mt CO_2eq. The contribution of CO_2, CH_4 and N_2O to the total CO_2eq emissions are 82.58%, 9.70% and 8.38%. District level variation in biomass power related GHG emissions is shown in Fig. 3.

If the biomass equivalent power (*i.e.* 7028 MW) were drawn from fossil fuels, annual GHG emissions from coal and natural gas would be 50.48 and 30.18 Mt CO_2eq. Considerable amount of GHG emissions reduction is possible if biomass replaces fossil fuels as power source.

4.4. Impact of GHG emissions on global surface temperature change

Using AGTP climate metric, impact of GHG emissions on global

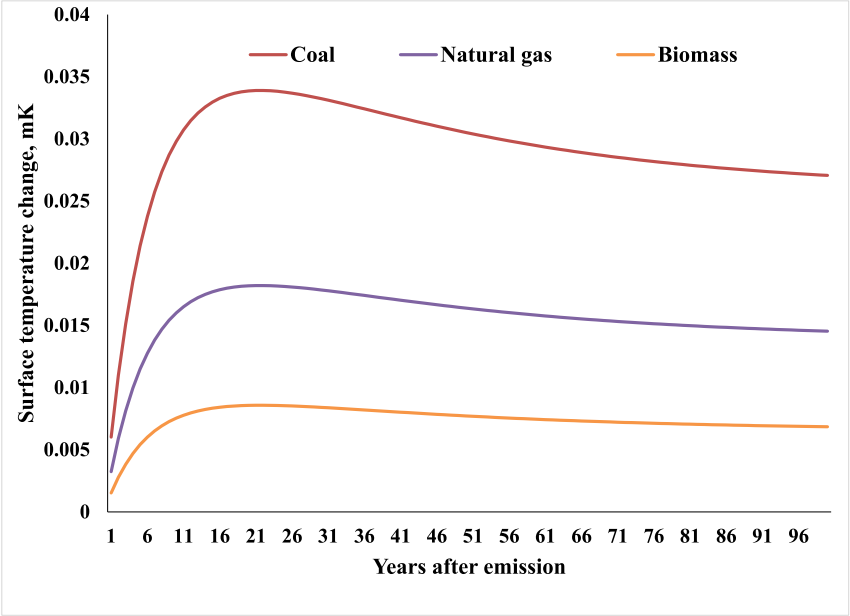

Fig. 5(a). Impact of CO_2 emissions on global surface temperature change over 100 years period.

surface temperature change from biomass power generation (in comparison with coal and natural gas) in the study area is assessed. The peak impact on temperature change due to CO_2, CH_4 and N_2O emissions are observed at 22, 10 and 26 years after the initial emissions. The year-by-year values of AGTP for a period of 100 year for CO_2, CH_4 and N_2O are given in the Supplementary material-S2.

Multiplying AGTP values of CO_2, CH_4 and N_2O with emissions values gives year-by-year impact on global surface temperature. Fig. 4 shows global surface temperature response of GHG emissions from biomass, coal and natural gas based power generation. At the end of 100 years, an initial single year's emissions from biomass, coal and natural gas-fired power generation in Uttar Pradesh, India would cause global surface temperature to rise by 7.49×10^{-3}, 2.72×10^{-2} and 1.48×10^{-2} mK. The peak temperature rises of 0.035, 0.024 and 0.011 mK are observed at 20, 15 and 16 years after the initial emissions for coal, natural gas and biomass. After the peak, temperature would then start decreasing and attain steady state (Fig. 4). It is observed that a single year's emissions from 1 MWh hour power generation using coal, natural gas and biomass would cause 4.10×10^{-7}, 2.40×10^{-7} and 1.25×10^{-7} mK rise in global surface temperature, 100 years after initial emissions. Replacing 1 MWh of coal and natural gas-fired power with an equivalent amount of biomass power could reduce global surface temperature rise by 2.85×10^{-7} and 1.15×10^{-7} mK, 100 years after initial emissions.

Individual influence CO_2, CH_4 and N_2O on global surface

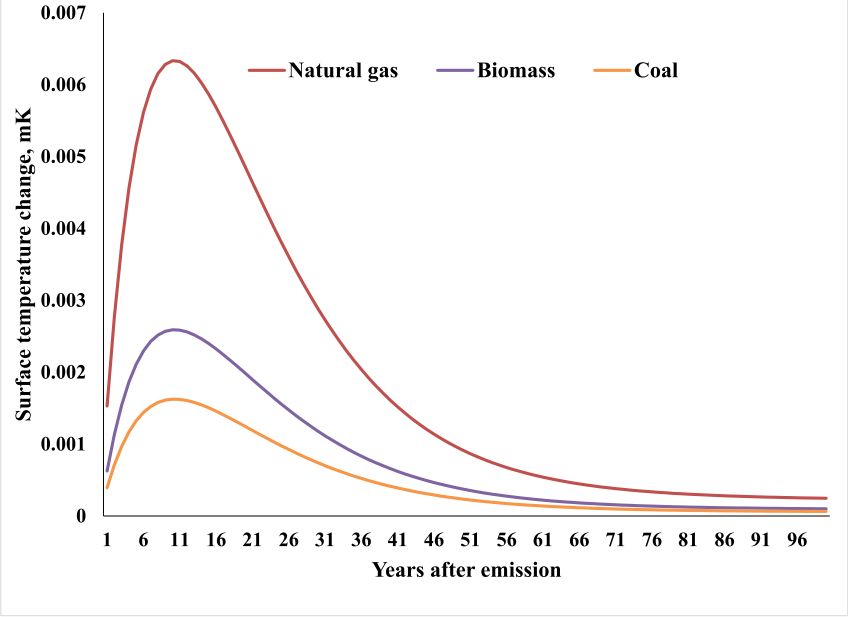

Fig. 5(b). Impact of CH_4 emissions on global surface temperature change over 100 years period.

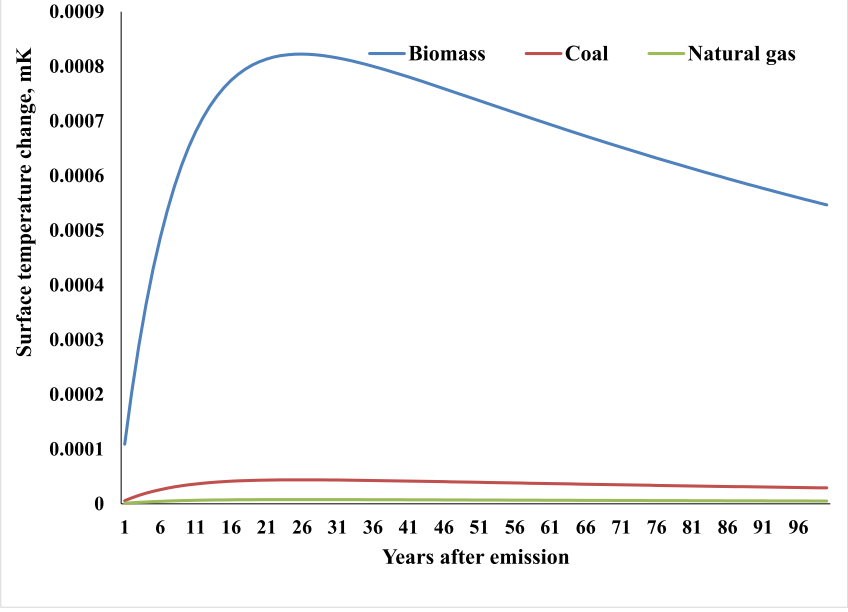

Fig. 5(c). Impact of N_2O emissions on global surface temperature change over 100 years period.

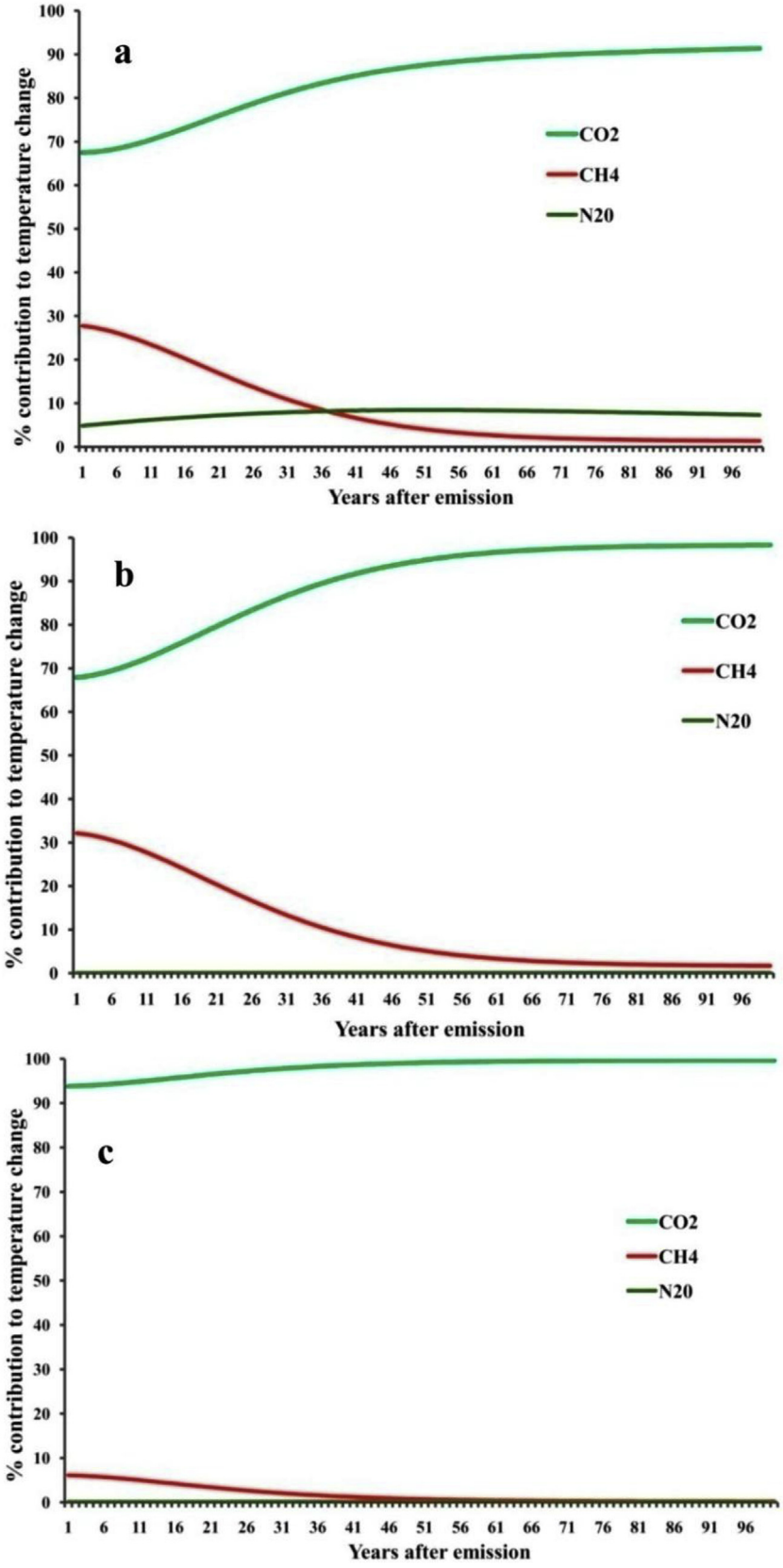

Fig. 6. Percentage contribution of CO_2, CH_4 and N_2O emissions to global surface temperature change over 100 years period (Fig. 6a: biomass system; 6b: natural gas system, and 6c: coal system).

temperature change is shown separately in Fig. 5a,b,c. If only CO_2 emission is considered, coal based power generation would have the highest impact on surface temperature change (Fig. 5a). Considering CH_4 emission alone, natural gas would have the highest impact on temperature change (Fig. 5b). This is because CH_4 emissions from natural gas-fired power generation is higher than biomass and coal. High CH_4 emissions could occur during mining and transport (leakage) processes. If only N_2O emissions is considered, biomass would have higher impact on temperature change than coal and natural gas (Fig. 5c). Biomass cultivation is associated with high N_2O emissions (mostly due to N-fertilizer application in agriculture) (Crutzen et al., 2016). Biogas system also emits considerable amount of N_2O. Efficient management of biomass production chain is important to reduce non-CO_2 emissions.

Timeline of impact of a particular GHG on temperature change is shown in Fig. 6. It is observed that CO_2 would have dominant impact on temperature change throughout the 100 year timeframe. The initial (year one) contribution of CO_2 to temperature change is about 67% in biomass (Fig. 6a) and natural gas systems (Fig. 6b) but almost 94% in coal system (Fig. 6c). The initial year impact of CH_4 on temperature change is 1/3 of the temperature change (Fig. 6a and b) in biomass and natural gas systems. The impact of CH_4 on temperature change decreases over time due to short its short lifetime (12.4 years). At the end of 100 years, CO_2 would have dominant impact on temperature rise (91.4%, 98.3% and 99.7% in biomass, natural gas and coal systems). The impact of N_2O on temperature rise would remain constant throughout the 100 years (5–7% in biomass and <1% in natural gas and coal) due to its relatively long lifetime (more than 100 years).

4.5. Sensitivity and uncertainty

Sensitivity and uncertainty in biomass resource and power potentials, GHG emissions and impact on temperature change are discussed below.

4.5.1. Variation in biomass resource and power potentials

Depending upon feedstock availability, characteristics and energy conversion technology, variations in biomass power potential could be expected. Such variations are also observed in the study region. In scenario-1 (low biomass availability factor and low conversion efficiency), biomass resources and power potentials in Uttar Pradesh are 36.35 Mt (about two times less than baseline estimate of 70.63 Mt) and 3427 MW (about 50% less than baseline estimate of 7028 MW). In scenario-2 (high biomass availability factor and high conversion efficiency), biomass resources and power potentials are 85.73 Mt (18% higher than baseline estimate of 70.63 Mt) and 9883 MW (29% higher than baseline estimate of 7028 MW). Annual biomass resource and power potentials in Uttar Pradesh, India thus could vary from 36.35 to 85.73 Mt and 3427–9883 MW.

4.5.2. Variation in GHG emissions

Under low and high biomass emission scenarios, annual GHG emissions are 8.01 and 25.90 Mt CO_2eq against 15.16 Mt CO_2eq at median emissions scenario. In all the cases, emissions from biomass power is less than coal (50.48 Mt CO_2eq) and natural gas (30.18 Mt CO_2eq).

4.5.3. Variations in global surface temperature change

Under low and high biomass emission factors, biomass power generation in Uttar Pradesh would cause surface temperature to rise by 4.04×10^{-3} and 1.30×10^{-2} mK, 100 years after initial emissions. A comparison with coal and natural gas are presented in Fig. 7. As shown in Fig. 7 maximum gain in climate change mitigation could be achieved under Biomass scenario-1 (low emission factor). Under high emission factor (Biomass scenario-2), impact of biomass power on surface temperature change is almost equal to natural gas-fired power generation (Fig. 7).

4.6. Scope and limitations of the present study

The present work explain a procedure to assess biomass resource and power potentials at local scale through a case study in Uttar Pradesh, India. The study also demonstrated potential application of AGTP climate metric in GHG emissions study of biomass energy. Current life cycle assessment (LCA) inventories of GHG emissions are based on GWP metric and unable to relate emissions

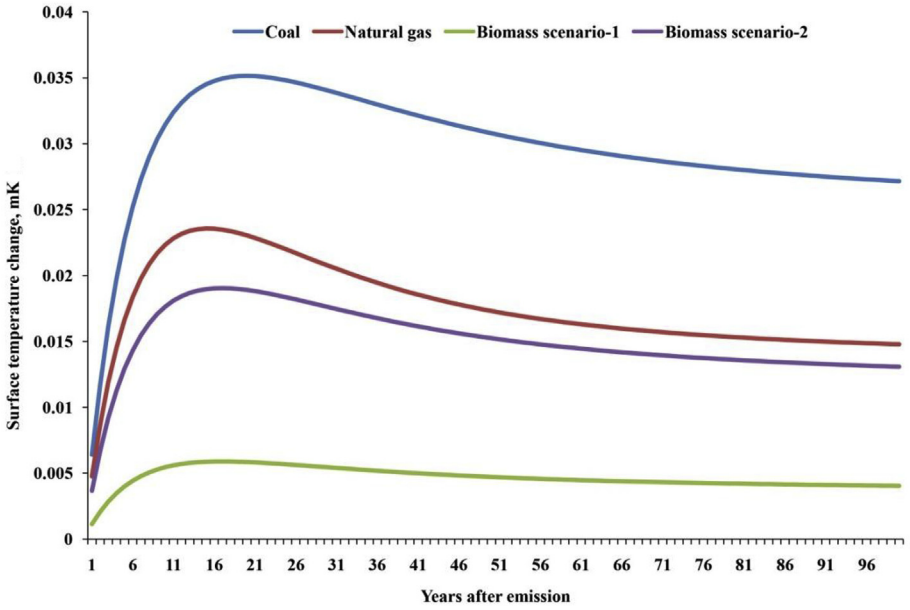

Fig. 7. Impact of GHG emissions on surface temperature change under different energy system scenarios.

with global surface temperature change. The present study can be useful to overcome this limitation. The estimated global surface temperature change per unit of power generation (mK per MWh in this study) can serve as reference for other regions to assess climate change mitigation potential of biomass resource. Site-specific GHG emissions inventories are recommended to minimize uncertainty associated with average global emissions values.

5. Conclusion

Biomass has often been regarded as a promising renewable resource to meet energy demand and mitigate climate change. However, impact of biomass power on global surface temperature is unclear. This paper, through a case study in Uttar Pradesh, India present biomass power and GHG emissions inventories in comparison with coal and natural gas. The state has a potential to generate 7028 MW of biomass power annually. Among the 75 districts of the state, 29 districts have biomass power potential >100 MW. Power density of biomass range between 0.10 and 0.25 Wm^{-2}. GHG emissions from biomass power generation is significantly less than coal and natural gas. The peak temperature rises after initial GHG emissions from coal, natural gas and biomass-fired power generation are observed at 20, 15 and 16 years. Biomass power has less impact on global surface temperature rise than coal and natural gas and replacing fossil fuels with biomass could contribute to climate change mitigation. Variation in spatio-temporal distribution and low power density could be delimiting factors in large-scale deployment of biomass power.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.02.194.

References

Blanco-Canqui, H., Lal, R., 2009. Crop residue removal impacts on soil productivity and environmental quality. Crit. Rev. Plant Sci. 28, 139–163.
Brahma, A., Saikia, K., Hiloidhari, M., Baruah, D.C., 2016. GIS based planning of a biomethanation power plant in Assam, India. Renew. *Renew. Sustain. Energ. Rev.* 62, 596–608.
BRAI, 2004. Biomass resource Atlas of India. http://lab.cgpl.iisc.ernet.in/atlas/Tables/Tables.aspx. (Accessed 23 November 2018).
Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wiser, R., Zhang, X., 2014. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, vol. 7. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 511–597.
Cardoen, D., Joshi, P., Diels, L., Sarma, P.M., Pant, D., 2015. Agriculture biomass in India: Part 1. Estimation and characterization. Resour. Conserv. Recycl. 102, 39–48.
CEA, 2018. Central electricity authority, India. http://www.cea.nic.in/reports/monthly/executivesummary/2018/exe_summary-03.pdf. (Accessed 12 June 2018).
Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145, 87–99.
Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009. Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resour. Conserv. Recycl. 53, 434–447.
Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W., 2016. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. In: Crutzen, P.J., Brauch, H. (Eds.), Paul J. Crutzen: A Pioneer on Atmospheric Chemistry and Climate Change in the Anthropocene, vol. 12. Springer, Cham, pp. 227–238.
DADF, 2017. Department of Animal Husbandry, Dairying and Fisheries. Government of India. http://dahd.nic. (Accessed May 2017).
de Castro, C., Ó, Carpintero, Frechoso, F., Mediavilla, M., de Miguel, L.J., 2014. A top-down approach to assess physical and ecological limits of biofuels. Energy 64, 506–512.
Dhinesh, B., Annamalai, M., 2018. A study on performance, combustion and emission behaviour of diesel engine powered by novel nano nerium oleander biofuel. J. Clean. Prod. 196, 74–83.
DLR, 2017. Department of land resources, government of India. http://dolr.nic.in/dolr/wasteland_atlas.asp accessed February 2017.
EIA, 2018. U.S. Energy information administration. https://www.eia.gov/beta/international/data/browser/#/?pa=000000001&c=ruvvvvvfvtvnvv1urvvvvfvvvvvfvvvou20evvvvvvvvvvnvvuvo&ct=0&ug=2&vs=INTL.44-2-IND-TJ.A&vo=0&v=H&end=2015&s=INTL.44-2-HKG-TJ.Ā~INTL.44-2-HND-TJ.Ā~INTL.44-2-HUN-TJ.A (accessed June 13, 2018).
Ferguson, A.R., 2008. The power density of ethanol from Brazilian sugarcane. In: Pimentel, D. (Ed.), Biofuels, Solar and Wind as Renewable Energy Systems, vol. 19. Springer, Dordrecht, pp. 493–498.
Gibbs, H.K., Johnston, M., Foley, J.A., Holloway, T., Monfreda, C., Ramankutty, N., Zaks, D., 2008. Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. Environ. Res. Lett. 3, 034001.
Giuntoli, J., Agostini, A., Caserini, S., Lugato, E., Baxter, D., Marelli, L., 2016. Climate change impacts of power generation from residual biomass. Biomass Bioenergy 89, 146–158.
Giuntoli, J., Caserini, S., Marelli, L., Baxter, D., Agostini, A., 2015. Domestic heating from forest logging residues: environmental risks and benefits. J. Clean. Prod. 99, 206–216.
Goel, V.L., Behl, H.M., 1996. Fuelwood quality of promising tree species for alkaline soil sites in relation to tree age. Biomass Bioenergy 10, 57–61.
Hiloidhari, M., Das, D., Baruah, D.C., 2014. Bioenergy potential from crop residue biomass in India. Renew. Sustain. Energy Rev. 32, 504–512.
ICRAF, 2016. The World Agroforestry Centre. Tree functional and ecological databases. http://www.worldagroforestry.org/output/tree-functional-and-ecological-databases (accessed March, 2016).
IEA, 2017. Bioenergy and biofuels. http://www.iea.org/topics/renewables/bioenergy/ (accessed March 02, 2018).
Iordan, C., Lausselet, C., Cherubini, F., 2016. Life-cycle assessment of a biogas power plant with application of different climate metrics and inclusion of near-term climate forcers. J. Environ. Manag. 184, 517–527.
Kammen, D.M., Sunter, D.A., 2016. City-integrated renewable energy for urban sustainability. Science 352, 922–928.
Ko, S., Lautala, P., Handler, R.M., 2018. Securing the feedstock procurement for bioenergy products: a literature review on the biomass transportation and logistics. J. Clean. Prod. 200, 205–218.
Kumar, A., Kumar, N., Baredar, P., Shukla, A., 2015. A review on biomass energy resources, potential, conversion and policy in India. Renew. Sustain. Energy Rev. 45, 530–539.
Liu, Z., Johnson, T.G., Altman, I., 2016. The moderating role of biomass availability in biopower co-firing—a sensitivity analysis. J. Clean. Prod. 135, 523–532.
McKendry, P., 2002. Energy production from biomass (part 2): conversion technologies. Bioresour. Technol. 83, 37–46.
Misri, B.K., 2017. Country pasture/forage resources profiles–India. http://www.fao.org/ag/agp/agpc/doc/counprof/india.htm accessed August, 2017.
MNRE, 2018. Annual Report 2017-2018. Ministry of New and Renewable Energy, India. https://mnre.gov.in/file-manager/annual-report/2017-2018/EN/content.html (accessed June 12, 2018).
MoA, 2017. Ministry of Agriculture and Farmers Welfare. Government of India. http://eands.dacnet.nic.in. accessed February, 2017.
Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), In Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, vol. 8. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–740.
NASA, 2015. Stubble burning in Punjab, India. https://visibleearth.nasa.gov/view.php?id=86982. (Accessed 11 March 2018).
NPP, 2018. National power portal, India. https://npp.gov.in/public-reports/cea/monthly/installcap/2018/MAY/capacity2-Northern-2018-05.pdf. (Accessed 12 June 2018).
Oreggioni, G.D., Singh, B., Cherubini, F., Guest, G., Lausselet, C., Luberti, M., Ahn, H., Strømman, A.H., 2017. Environmental assessment of biomass gasification combined heat and power plants with absorptive and adsorptive carbon capture units in Norway. Int. J. Greenh. Gas. Con. 57, 162–172.
Sander, B.O., Samson, M., Buresh, R.J., 2014. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. Geoderma 235, 355–362.

Schlömer, S., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., Schaeffer, R., Sims, R., Smith, P., Wiser, R., 2014. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Annex III. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1329–1356.

Schweier, J., Molina-Herrera, S., Ghirardo, A., Grote, R., Díaz-Pinés, E., Kreuzwieser, J., Haas, E., Butterbach-Bahl, K., Rennenberg, H., Schnitzler, J.P., Becker, G., 2017. Environmental impacts of bioenergy wood production from poplar short-rotation coppice grown at a marginal agricultural site in Germany. GCB Bioenergy 9, 1207–1221.

Shine, K.P., Fuglestvedt, J.S., Hailemariam, K., Stuber, N., 2005. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Clim. Change 68, 281–302.

Singh, J., 2017. Management of the agricultural biomass on decentralized basis for producing sustainable power in India. J. Clean. Prod. 142, 3985–4000.

Singh, V., Toky, O.P., 1995. Biomass and net primary productivity in *Leucaena, Acacia* and Eucalyptus, short rotation, high density ('energy') plantations in arid India. J. Arid Environ. 31, 301–309.

Smil, V., 2010. Power Density Primer: understanding the spatial dimension of the unfolding transition to renewable electricity generation (Part I–Definitions). http://vaclavsmil.com/wp-content/uploads/docs/smil-article-power-density-primer.pdf. (Accessed September 2017).

Spath, P.L., Mann, M.K., Kerr, D.R., 1999. Life Cycle Assessment of Coal-Fired Power Production. NREL, Colorado, USA.

Spath, P.L., Mann, M.K., 2000. Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System. NREL, Colorado, USA.

UNEP/SETAC, 2016. Global Guidance for Life Cycle Impact Assessment Indicators, vol. 1. United Nations Environment Programme.

UNFCCC, 2018. Local data for wood density. https://cdm.unfccc.int/filestorage/B/7/Y/B7Y5L3VPMSJN0ODWU2HARC41Z9XG8I/ref%2016a%20Local%20data%20for%20wood%20density%20.pdf?t=Tkx8cDVmazFufDDkDc6shz83UsgZITxuDfVL. (Accessed 11 March 2018).

Vijayakumar, K., Safai, P.D., Devara, P.C., Rao, S.V., Jayasankar, C.K., 2016. Effects of agriculture crop residue burning on aerosol properties and long-range transport over northern India: a study using satellite data and model simulations. Atmos. Res. 178, 155–163.